Journal of Natural Gas Science and Engineering 29 (2016) 497–505

Contents lists available at ScienceDirect

Journal of Natural Gas Science and Engineering

journal homepage: www.elsevier.com/locate/jngse

# The dynamical response characteristics of elastic–plastic coal under dynamic load

Feng Li*, Yaguang Zhang, Jianrong Liu, Liang Zhang, Shuhao Fang

*Faculty of Resource and Safety Engineering, China University of Mining and Technology (Beijing), Beijing 100083, China*

ARTICLE INFO

*Article history:*
Received 24 August 2015
Received in revised form
10 November 2015
Accepted 26 January 2016
Available online 29 January 2016

*Keywords:*
Dynamic loading
Elastic-plastic coal
Unloading waves
Tensile stress

ABSTRACT

At present, it has been confirmed that tensile stress can be generated in coal bodies through instantaneous unloading, which leads to severe damage in certain areas of the coal. However, the process for the generation of this tensile stress is still unclear. In this study, by taking the elastic–plastic coal in the front of the tunneling face and the rock cross-cut coal uncovering region as examples, and by applying the rules of reflection and transmission to the stress waves, the concrete propagation process of stress waves in coal under dynamic loading was examined. At the same time, the formation and acting mechanisms of the tensile stress waves under the interaction of the loading and unloading stress waves were studied. The results indicated that compression-shear, tension, and tension-shear failures in the elastic–plastic coal were evident, under the role of the instantaneous loading and unloading. Due to the fact that the wave impedance of the coal tended to distribute unevenly in the front of the tunneling face, the loading and unloading stress waves were thereby transmitted and reflected in the propagation process of the coal body, and formed unloading stress waves. The tensile stress generated in the coal under the unloading waves, which were prone to severe damage to coal body, led to dramatic increases of the gas desorption rate, as well as a significant rising of the gas pressure. These results led to the occurrences of the coal and gas outburst accidents. Therefore, the development process of the coal and gas outbursts was determined to have begun on the inside of the coal, then to gradually develop towards the tunneling face. Multi-beam unloading waves were formed by the instantaneous unloading of the blast-hole wall, as well as the pressure released around the coal. Radial tensile stress waves in the coal were prominent, under the role of the unloading waves, which led to tension failure in the coal, which in turn generated circumferential cracks. This caused the spallation phenomena of the coal around the outburst-hole wall during the process of the coal and gas outbursts. The conclusions of this study have important theoretical guiding significance for the prevention of coal and rock dynamic disasters.



## 1. Introduction

The geological factors effecting coal and gas outbursts mainly include the buried depth, rock permeability, structure complexity, and development level of the tectonic coal (Li and Lian, 2007; Wei et al., 2007). According to the available statistics, coal and gas outburst accidents in China mainly occur in the region of geological structures, and the development level of the tectonic coal is one of the essential conditions (Cao et al., 2001; Guo et al., 2002). There were found to be obvious anomaly areas of tectonic stress near the geological structure faults, and there was also found to be superposition with the stress concentration resulting from the later excavations (Gao et al., 2015; Burra et al., 2014a,b). The micro-pores of the tectonic coal showed good development, high adsorption capacity, and a low permeability rate (Gao, 2013; Wierzbicki and Mlynarczuk, 2013). Therefore, the failure zone of the enclosed geological structures before near exposure maintained higher surrounding rock stress and gas pressure, and formed an exceptionally high stress and gas pressure gradient (Skoczylas, 2012; Zhang et al., 2013; Cheng et al., 2012; Han et al., 2007; Hou et al., 2012). The increase of the coal gas and tectonic stress enhanced the potential energy accumulation ratio, and the potential energy for the outburst initiation was increased due to the tectonic stress (An and Cheng, 2014; Mu and Qi, 2012). The occurrence of large coal and gas outbursts under the condition of the instantaneous unloading of the coal were found to be the results of mining and other human

* Corresponding author.
*E-mail address:* lifengcumtb@126.com (F. Li).

http://dx.doi.org/10.1016/j.jngse.2016.01.032
1875-5100/

factors (Han et al., 2012; Xu et al., 2014; Cheng et al., 2013; Jin et al., 2012; Chen, 2011).

Currently, it has been determined that tensile stress can be generated in coal bodies under the role of instantaneous unloading, which leads to severe damage in certain areas of the coal. All of the reserved rocks first experience the process of compressive stress, and then tensile and radial stresses during the processes of blasting and excavation. The tensile stress caused by the instantaneous unloading of the blasts, along with the in-situ stress, are important factors involved in the damages to the rock masses (Zhu, 2010; Chu et al., 2012; Chen et al., 2011). When structure zones existed in front of the tunneling faces, the explosive stress waves were reflected at the interface between the raw and tectonic coal. The reflection wave was strengthened to generate tensile stress, which led to tensile failure (Chang et al., 2014; Cai et al., 2014; Yang et al., 2013a,b), and caused severe damages to the coal body.

Overall, the stress wave propagation, and the interaction between the loading and unloading waves in the coal, had great significance in regards to the damage caused to the coal under the role of dynamic load. However, the understanding of the concrete propagation process, as well as the interaction mechanism of the stress waves in tectonic coal, are still relatively lacking, especially the studies regarding the generation and role mechanism of tensile stress waves during the interaction between the loading and unloading waves.

In this study, the tectonic coal in front of the tunneling face and the rock cross-cut coal uncovering region were taken as examples. Using the transmission and reflection rules of the stress wave as a basis, the concrete propagation process of stress waves in tectonic coal under dynamic load was examined. Also, the generation and role mechanism of tensile stress waves during the interaction between the loading and unloading waves were also evaluated. The dynamic damage mechanism of the coal was analyzed, and the results have important significance for the prevention of coal and rock dynamic disasters.

## 2. Regional distribution characteristics of the coal bodies

### 2.1. Regional distribution characteristics of elastic–plastic coal in front of the tunneling faces

Due to the effects caused by roadway driving, there was obvious stress concentration in coal, which caused damages to the coal body, and then the formation of plastic coal during tunneling face advancing. The coal body in front of tunneling face consisted of plastic and elastic coal.

In accordance with the regional distribution state of the coal in front of the tunneling face as shown in Fig. 1, the following can be seen: (1) The coal body in front of the tunneling face consisted of elastic and plastic coal; (2) Interface $X_a$ between the elastic coal and plastic coal was located between areas B and C, and the 3rd and 4th areas in front of the tunneling face.

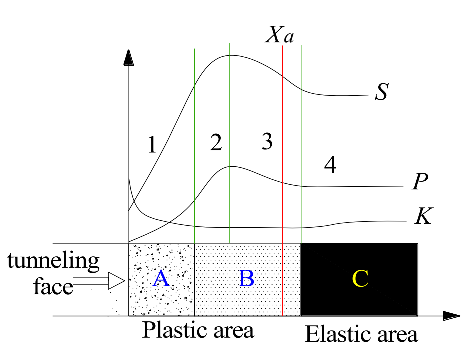


**Fig. 1.** The distribution of in-situ stress, gas pressure, and permeability of the coal in front of the tunneling face.

There was obvious regional distribution characteristics observed for the in-situ stress, gas pressure, and permeability of the coal in front of the tunneling face as follows:

(1) The distribution of area *S* for in-situ stress was as follows: area A was the stress relief area; area B was the stress concentration area; and area C was the original rock stress area.
(2) The distribution of area *K* for the coal permeability was as follows: The 1st, 2nd, 3rd, and 4th areas had high permeability, increased permeability, decreasing permeability, and original rock permeability, respectively.
(3) The distribution of area *P* for the gas pressure was as follows: The 1st area was the decreasing area of the gas pressure; the 2nd and 3rd areas were the increasing area of the gas pressure; and the 4th area was the area of the original rock gas pressure.

### 2.2. Regional distribution characteristics of the tectonic coal in front of tunneling face

If a geological formation existed (such as a fault, syncline, anticline, fold, and so on) in front of the tunneling face, it was considered that the coal there consisted of plastic, elastic, tectonic, and raw coal. Due to the impact of driving, as well as the role of geologic structures, in-situ stress, gas pressure, and permeability of the coal in front of the tunneling face obviously appeared to have regional distribution characteristics, as shown in Fig. 2, and the following was determined:

(1) The $\sigma$ area distribution of in-situ stress was as follows: Area A of the plastic coal contained the stress relief and stress concentration areas; area B of the elastic coal contained the stress concentration and original rock stress areas; area C of the tectonic coal contained the stress concentration and stress relief areas; and area D of the raw coal contained the stress concentration and original rock stress areas.
(2) The area *K* distribution of the coal permeability had an obvious corresponding relationship to the distribution of the in-situ stress. The permeability of the coal in front of the tunneling face had a changing trend of: decrease-increase-decrease-stability.
(3) The *P* area distribution of gas pressure had an obvious corresponding relationship to the distribution of the in-situ stress, as well as the distribution of the coal permeability. The gas pressure of the coal in front of tunneling face showed a changing trend, which was increase-decrease-increase-stability.

## 3. Loading and unloading waves propagation processes in the coal body

### 3.1. The propagation of the loading and unloading stress waves in the elastic–plastic coal in front of tunneling face

The coal in front of tunneling face consisted of elastic and plastic coal (Fig. 1). The wave impedance on both sides of the elastic–-plastic interface in front of tunneling face was not equal, and the wave impedance of the plastic coal $\rho_0 c_l$ was smaller than that of the elastic coal $\rho_0 c_e$. It could be obtained that the $c_l$ (wave velocity of plastic wave) was less than the $c_e$ (wave velocity of elastic coal).